DESKTOP, 20-MW SUPERRADIANCE FEL AT THz FREQUENCIES

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Abstract

We numerically study the generation of periodically bunched electrons from a 6 MeV photocathode electron gun driven by a beat-wave laser with a beat frequency at THz frequencies. We then numerically injected the electrons into a single-pass FEL undulator. Due to the prebunched electrons, the quick build-up of the FEL power can overcome the space-charge debunching force. With nominal beam parameters and an initial bunching factor of 0.2, the FEL can reach nearly 20-MW saturation power at 4.7 THz in a ~0.5 m distance in the wiggler. The length of this 20-MW THz FEL, from the beginning of the electron gun to the end of the undulator, is less than a meter.

INTRODUCTION

A compact, high-power radiation source at THz frequencies is desirable for many applications. A free-electron laser (FEL) is capable of generating high-power radiation over a broad electromagnetic spectrum. Implementing a long-wavelength FEL is long thought to be easier than implementing a short-wavelength one. However it is much harder for a self-amplified-spontaneous-emission (SASE) FEL at THz frequencies to reach saturation due to the strong space-charge force in the low-energy beam. In this paper, we study a technique of injecting periodically pre-bunched electrons into a short FEL undulator to achieve high-power electron superradiance at THz frequencies.

To facilitate the discussion, we briefly describe in the following the theory of electron superradiance based on Gover's formulation [1]. In general, the spectral energy of the radiation from an electron bunch with a bunch length τ_b and an electron number N_b is expressed by the equation

$$(dW/d\omega)_{SR} = N_b^2 (dW/d\omega)_1 M_b^2(\omega)\,, \quad (1)$$

where $(dW/d\omega)_1$ denotes the spectral energy emitted from a single electron with W being the radiation energy and ω being the angular frequency of the radiation, $M_b(\omega)$ is the Fourier transform of the electron pulse-shape function with a unitary peak amplitude. If the radiating electron beam contains N_{pb} such electron bunches repeating at a rate $\omega_{pb}/2\pi$, the total radiated spectral energy becomes

$$(dW/d\omega)_{SR,pb} = N_b^2 N_{pb}^2 (dW/d\omega)_1 M_b^2(\omega) M_{pb}^2(\omega)\,, \quad (2)$$

where

$$\left|M_{pb}(\omega)\right|^2 = \sin^2(N_{pb}\pi\omega/\omega_{pb})/[N_{pb}^2 \sin^2(\pi\omega/\omega_{pb})], \quad (3)$$

is the coherent sum of the radiation fields from all the micro-bunches and has a unitary peak amplitude at the frequencies $\omega = m\omega_{pb}$ (m = 1, 2, 3…). For a short electron bunch, $M_b^2(\omega)$ is usually a broad-band function. The spectral linewidth of $M_{pb}^2(\omega)$ at $\omega = m\omega_{pb}$ is given by $\sim \omega_{pb}/N_{pb}$, which, for a large number of periodic electron bunches, could be much narrower than the intrinsic spectral linewidth of a radiation device governed by $(dW/d\omega)_1$. Since electrons are discrete particles, the term $M_b(\omega)M_{pb}(\omega)$, describing the degree of electron bunching at the frequency ω, is sometimes called the electron bunching factor.

Previously we have proposed the use of a laser beat wave to excite periodic emissions of electrons from the photocathode of an electron accelerator [2]. In this paper, we study a single-pass THz FEL driven by such a laser-beat-wave (Labew) photocathode accelerator. The system configuration of this study is depicted in Fig. 1, consisting of three major components, a RF photocathode gun, an emittance-compensating solenoid, and a helical undulator. The periodically bunched electrons are excited by a laser beat wave at the photocathode, accelerated by a 1.6-cell S-band accelerator, and injected into a helical undulator to generate electron superradiance.

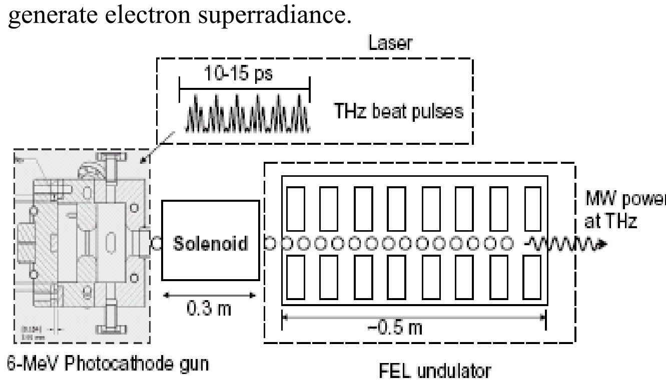


Figure 1: The system configuration of the desktop THz superradiance FEL driven by a Labew photocathode gun. Periodically prebunched electrons are injected into a short FEL undulator to generate intense electron superradiance.

Labew PHOTOCATHODE GUN

In this section, we study the acceleration of periodically bunched electrons in the BNL/UCLA/SLAC 1.6-cell S-band photocathode electron gun [3] by using the space charge tracking code ASTRA [4]. This gun is being built at the National Synchrotron Radiation Research Centre, Taiwan. The gun has a total acceleration length of 12.6 cm. We operate the gun at a peak acceleration gradient of 140 MV/m. The electrons are emitted from the photocathode with a radial distribution within a 0.75-mm rms radius. We equally divided 1-nC charges into 44 micro-bunches over 10 ps duration. The 227-fs micro-bunch separation is set to be six sigma of the Gaussian bunch length. A total of 14080 macro-particles were used in the simulations. At the gun output, we obtained average beam energy of 6.3 MeV with energy spread 0.3%, rms beam emittance of 2.8 π-mm-mrad, and rms beam radius of 1.3 mm. Figure 2 show the histogram of the accelerated electron bunches along the longitudinal direction, z. The longitudinal distribution of the electrons shows redistribution after acceleration. It is interesting to see that a significant portion of the output beam still shows obvious microbunches with a bunch separation of ~230 fs. Although the leading part of the beam retains the periodic bunching, the trailing part has no apparent bunching features. The particle redistribution is primarily due to the uneven acceleration fields seen by on-axis and off-axis electrons. Reducing the initial beam diameter can significantly improve the periodic bunching at the gun exit but the space-charge force will start to affect the microbunches for a too small starting beam size.

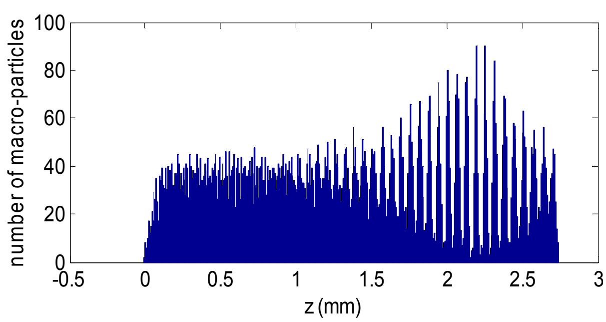


Figure 2: The electron distributions at the exit of the photocathode gun. The leading part of the beam retains periodic bunching, whereas the trailing part has no apparent bunching features.

The degree of electron bunching can be better described from the magnitude of the bunching factor $|M_b(\omega)M_{pb}(\omega)|$. We plot is Figure 3 the values of $|M_b(\omega)M_{pb}(\omega)|$ versus frequency before and after the acceleration of the periodically loaded beam. It is seen in Fig. 3(a) that the periodic bunches are nicely loaded at the cathode with a bunching factor of ~0.6 at 4.35 THz. In Fig. 3(b), the redistribution of the particles at the gun output causes some frequency broadening and magnitude reduction to the bunching factor. The fundamental frequency of the peak bunching is also shifted from 4.35 THz to 4.72 THz due to velocity bunching in the accelerator. Nevertheless the bunching factor is only reduced from 0.6 to 0.2 at the fundamental frequency. In the next section, we show that this reduction of the bunching factor does not prevent a THz superradiance FEL from reaching saturation in a short 0.5 m distance.

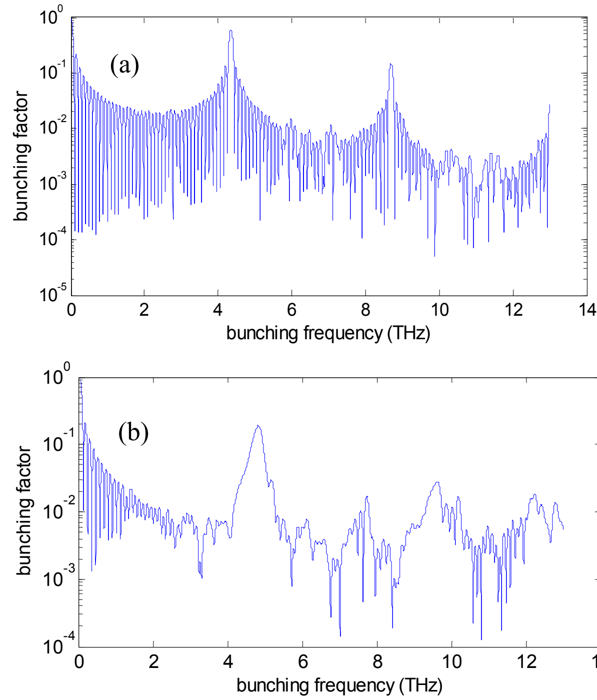


Figure 3: The bunching factor of the periodically loaded electron beam (a) before and (b) after acceleration in the photocathode gun. The space-charge and the acceleration forces redistribute the electrons during acceleration and result in spectral broadening and magnitude reduction to the bunching factor.

DESKTOP SUPERRADIANCE FEL

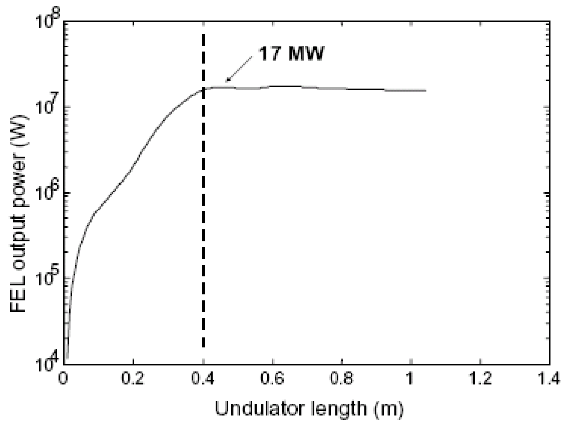
The FEL undulator in our choice is a helical undulator. The undulator has a period of 1.5 cm, a peak undulator field of 8.3 kG, and an undulator parameter of 0.82. Before sending the electrons into the FEL undultor, we use a solenoid to compensate the emittance growth and focus electrons before injecting the electrons into the undulator. The solenoid has a peak field of 2.6 kG centred at 25 cm from the gun cathode. The solenoid field drops to ~1% of its peak value at a location 17 cm from its centre. The entrance of the FEL undulator is positioned at 60 cm from the gun cathode. At the entrance of the undulator, the beam emittance is degraded to about 5.3 π-mm-mrad and the beam radius is focused to 0.15 mm.

We simulated the FEL performance by using the computer code GENESIS [5]. Table I summarizes the system parameters used for our simulation.

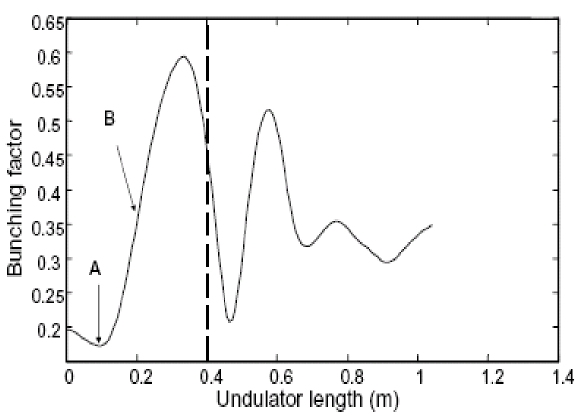
Table I. System parameters for the FEL simulated in GENESIS

<table>
<tr><td colspan="6">Electron Beam Parameters at Injection</td></tr>
<tr><td>bunching factor</td><td>total charge</td><td>rms beam energy</td><td>rms energy spread</td><td>rms emittance</td><td>rms beam radius</td></tr>
<tr><td>0.2</td><td>1 nC over 10 ps</td><td>6.3 MeV</td><td>0.3%</td><td>2.8 π-mm-mrad</td><td>0.15 mm</td></tr>
<tr><td colspan="6">Undulator Design Parameters (helical type)</td></tr>
<tr><td colspan="2">period</td><td colspan="2">gap</td><td colspan="2">peak field</td></tr>
<tr><td colspan="2">1.5 cm</td><td colspan="2">8 mm</td><td colspan="2">8.3 kG</td></tr>
</table>

The FEL radiation wavelength is 76 μm. Figure 4(a) shows the FEL power growth as a function of the undulator length. It is seen that the FEL quickly reaches saturation at ~17 MW within a distance of 0.4 m from the undulator entrance. We also tried the simulation for a linear undulator (hybrid type) with the same undulator period and peak undulator field, obtaining a saturation power of 13 MW at 0.8 m from the undulator entrance. The results are somewhat sensitive to the initial beam size. For most situations with an initial beam radius > 1 mm, the saturation power of the FEL predicted by GENESIS is on the order of a few kW. As a test, we also tried the FEL simulations without any initial bunching and found only spontaneous noises are generated from the FEL undulator.



(a)



(b)

Figure 4: (a) FEL power versus undulator length in a helical undualtor. The FEL power quickly reaches the saturation power of 17 MW at 0.4 m from the entrance of the undulator. (b) The electron bunching factor as a function of the undulator length. Initially the electrons are debunched in the region marked by A due to the space charge force. Owing to the quick build-up of the FEL power, the electrons overcome the debunching force and form tight bunches in the region marked by B.

To understand the FEL build-up process, we studied the variation of the bunching factor as a function of the undulator length. As seen by Fig. 4(b), initially the electrons are debunched in the region marked by A due to the space charge force. Owing to the quick build-up of the FEL power, the electrons overcome the debunching force and form tight bunches in the region marked by B. The increased bunching factor in turn helps the FEL to reach saturation in a short distance. Because the space charge force initially debunches the beam to a bunching factor of ~0.1, we found from our simulation that the FEL can reach the saturation power in ~0.5 m as long as the initial bunching factor is > 0.1.

CONCLUSIONS

A single-pass FEL driven by laser-prebunched electrons can be a promising radiation source. We simulated the performance of a Labew photocathode gun. With 44 periodic Gaussian bunches loaded at the cathode over 10 ps, the bunching factor of the 6.3-MeV output beam is slightly reduced from an initial value of 0.6 to 0.2 at the fundamental bunching frequency. The debunching is a consequence of the redistribution of electrons under the space charge force and the acceleration force.

By using the beam parameters generated from the gun simulation, we studied the performance of a single-pass THz FEL with a helical unduator. The FEL power quickly builds up to a saturation power of 17 MW within a distance of 0.4 m. The total length from the gun cathode to the end of the FEL undulator is merely 1 m. This quick generation of the FEL power suggests the potential of implementing a desktop FEL at THz frequencies by using the Labew accelerator technology. Our study also shows that it is unlikely to achieve saturation for a single-pass FEL by using such a low-energy driving beam without initial bunching, because the strong space charge force prevents the electrons from bunching.

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